Fermilab

Proton Driver, Superbeam & Neutrino Factory

Particle physics motivation for a new generation of multi-GeV proton sources providing multi-MW beams → neutrino oscillations

Context: Fermilab long-range plan … but the physics motivation for a new generation of Proton Drivers (Neutrino Superbeams and a Neutrino Factory) is not laboratory specific.

Neutrino Oscillations are Exciting

Stunning atmospheric-, solar-, and reactor-neutrino results have established that neutrinos have nonzero masses and mixings

The Standard Model needs modification to accommodate neutrino mass terms, which require either the existence of right-handed neutrinos ($\rightarrow$ Dirac mass terms), or a violation of lepton number conservation ($\rightarrow$ Majorana mass terms), or both.

We know that neutrino masses & mass splittings are tiny compared to the masses of the other fundamental fermions. This suggests radically new physics, which perhaps originates at the GUT or Planck Scale, or indicates the existence of new spatial dimensions.

Whatever the origin of the observed neutrino masses & mixings is, it will certainly require a profound extension to our picture of the physical world.

Neutrino Oscillation: Mixing Matrix 1

Within the framework of 3-flavor mixing, the 3 known flavor eigenstates (ν_e, ν_μ, ν_τ) are related to 3 neutrino mass eigenstates (ν_1, ν_2, ν_3) :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 3\times 3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

We know that U_{MNS} is very different from the CKM Matrix

$$\begin{pmatrix} \text{large} & \text{large} & \text{small/tiny ?} \\ \text{large} & \text{large} & \text{large} \\ \text{large} & \text{large} & \text{large} \end{pmatrix}$$

$$\begin{pmatrix} \sim 1 & \text{small} & \text{tiny} \\ \text{small} & \sim 1 & \text{tiny} \\ \text{tiny} & \text{tiny} & \sim 1 \end{pmatrix}$$

Neutrino Oscillation: Mixing Matrix 2

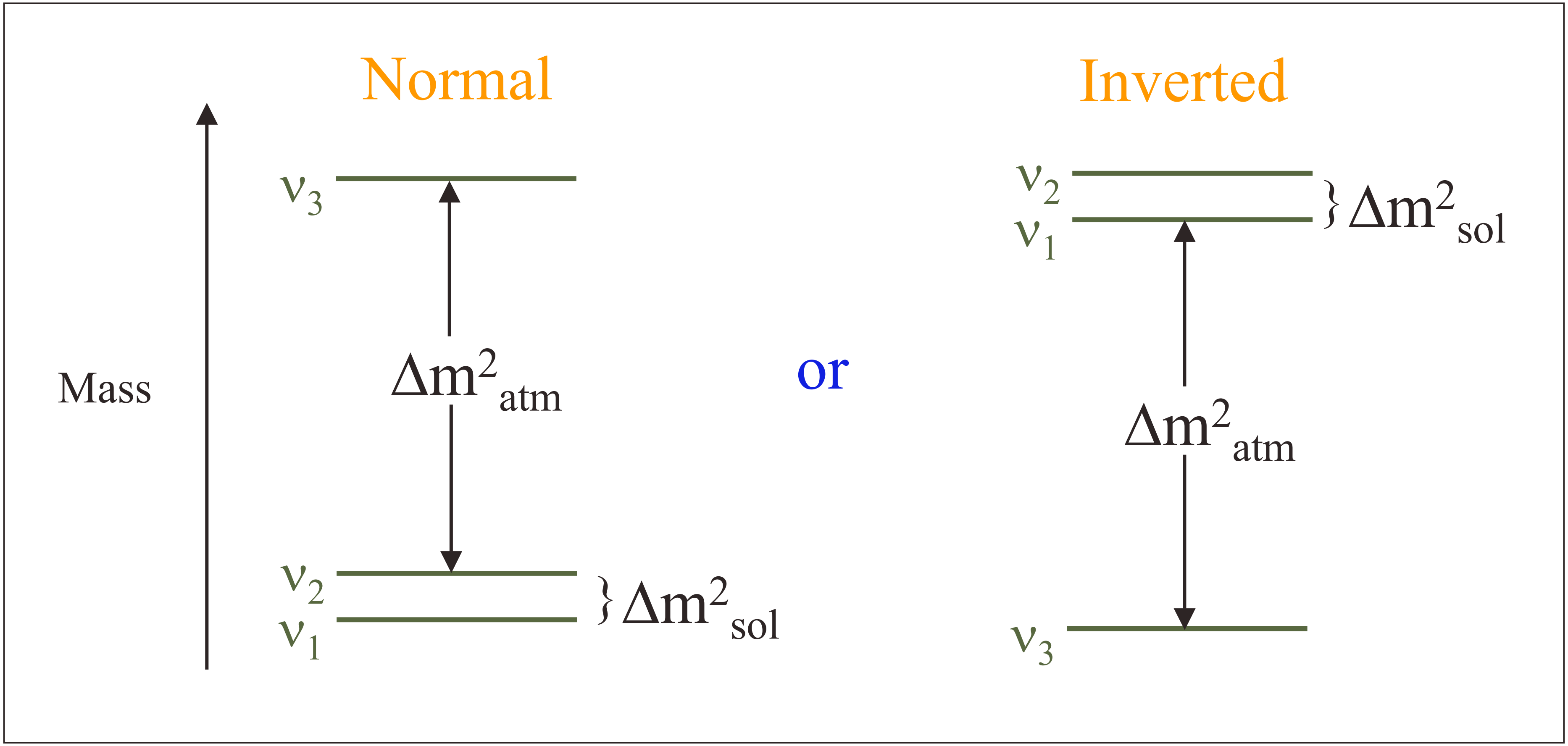
In analogy with the CKM matrix, U_{MNS} can be parameterized using 3 mixing angles (θ_{12} , θ_{23} , θ_{13}) and one complex phase (δ) :

$$\begin{pmatrix} C_{12}C_{23} & S_{12}C_{13} & S_{13}\,e^{-i\delta} \\ \begin{array}{c}-S_{12}C_{23} \\ -C_{12}S_{23}\,S_{13}\,e^{i\delta}\end{array} & \begin{array}{c}C_{12}C_{23} \\ -S_{12}C_{23}\,S_{13}\,e^{i\delta}\end{array} & S_{23}C_{13} \\ \begin{array}{c}S_{12}S_{23} \\ -C_{12}C_{23}\,S_{13}\,e^{i\delta}\end{array} & \begin{array}{c}-C_{12}S_{23} \\ -S_{12}C_{23}\,S_{13}\,e^{i\delta}\end{array} & C_{23}C_{13} \end{pmatrix}$$

We do not know the values of θ_{13} or the CP phase δ. If θ_{13} and δ are non-zero, there will be CP Violation in the neutrino sector.

Neutrino Oscillation: Mass Spectra 1

The oscillations are driven by the mass splittings: $\Delta m^2_{ij} \equiv m^2_i - m^2_j$



$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ eV^2$, $\quad |\Delta m^2_{atm}| \cong 2.5 \times 10^{-3}\ eV^2$

Neutrino Oscillation: Mass Spectra 2

The pattern of neutrino masses (normal or inverted) will provide us with clues to the underlying physics.

Generically, SO(10) grand unified models favor .

is un-quark-like, and would probably involve a lepton symmetry with no quark analogue: for example: $L_e - L_\mu - L_\tau$ conservation.

The neutrino mass hierarchy (normal or inverted) & hence the sign of Δm^2_{atm} is important !

Neutrino Oscillation Probabilities

The full expressions for the flavor transition probabilities are messy …

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m_{ij}^2 \ L / 4E) + 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m_{ij}^2 \ L / 2E)$$

We know that : $|\Delta m_{sol}^2| \le O(10^{-4})\ eV^2 \quad \ll \quad |\Delta m_{atm}^2| > 10^{-3}\ eV^2$

Since $|\Delta m_{32}^2| >> |\Delta m_{21}^2|$ we can gain some insight by neglecting terms driven by Δm_{21}^2.
For neutrinos of energy E propagating a distance L in vacuum :

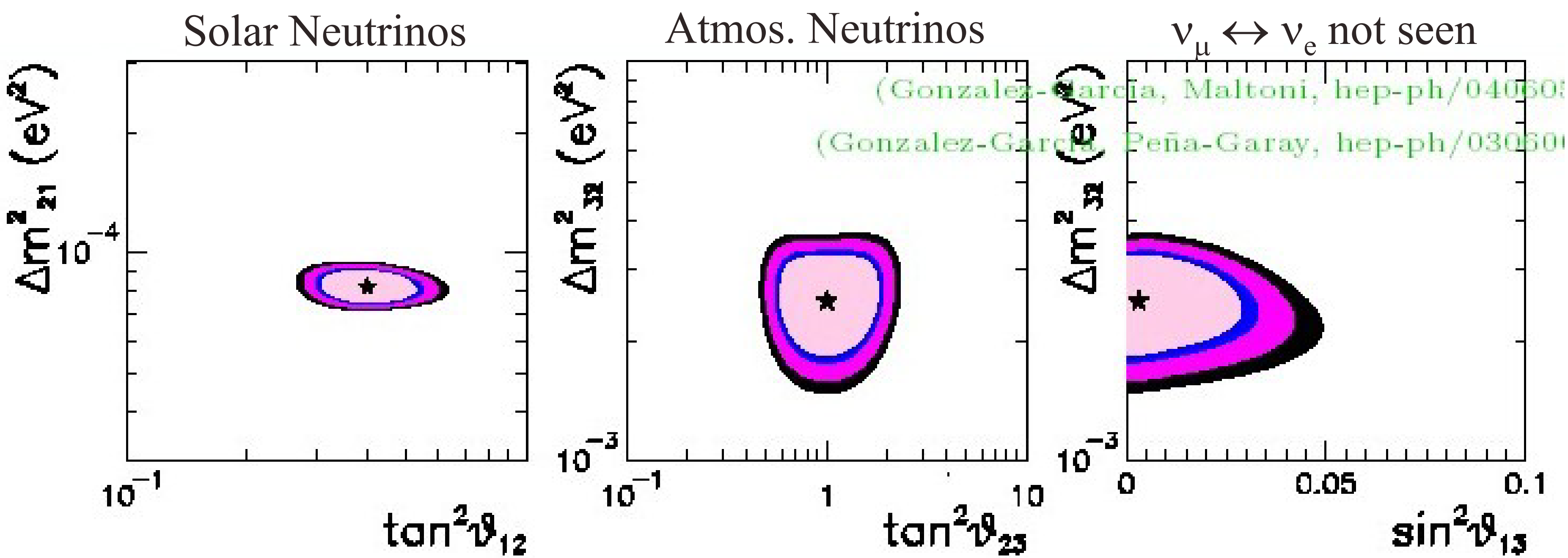
$$P(\nu_e \leftrightarrow \nu_\mu) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \ \sin^2(1.267\ \Delta m_{32}^2 L / E)$$

$$P(\nu_e \leftrightarrow \nu_\tau) \approx \cos^2\theta_{23} \sin^2 2\theta_{13} \ \sin^2(1.267\ \Delta m_{32}^2 L / E)$$

$$P(\nu_\mu \leftrightarrow \nu_\tau) \approx \sin^2 2\theta_{23} \cos^4\theta_{13} \ \sin^2(1.267\ \Delta m_{32}^2 L / E)$$

Neutrino Oscillation Parameters

From the solar-, atmospheric-, and reactor-neutrino data we already know a lot about the mixing matrix and mass splittings:



… but note that we have only an upper limit on θ_{13}, and know nothing about δ

Neutrino Oscillations and Physics at High Mass Scales

		$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
	SO(10)		
$\Delta m^2_{13} > 0$	Goh, Mohapatra, Ng [40]	0.18	0.13
	Orbifold SO(10)		
"typical"	Asaka, Buchmüller, Covi [41]	0.1	0.04
	SO(10) + flavor symmetry		
prediction	Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
	Blazek, Raby, Tobe [43]	0.05	0.01
	Kitano, Mimura [44]	0.22	0.18
of all*	Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
	Maekawa [46]	0.22	0.18
Type-I	Ross, Velasco-Sevilla [47]	0.07	0.02
	Chen, Mahanthappa [48]	0.15	0.09
GUT	Raby [49]	0.1	0.04
	SO(10) + texture		
models	Buchmüller, Wyler [50]	0.1	0.04
	Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
	Flavor symmetries		
inverted	Grimus, Lavoura [52, 53]	0	0
	Grimus, Lavoura [52]	0.3	0.3
hierarchy	Babu, Ma, Valle [54]	0.14	0.08
	Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
requires*	Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
	King, Ross [57]	0.2	0.15
	Textures		
"more	Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
	Lebed, Martin [59]	0.1	0.04
flavor	Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
	Ibarra, Ross [61]	0.2	0.15
structure"	*3 × 2 see-saw*		
	Appelquist, Piai, Shrock [62, 63]	0.05	0.01
	Frampton, Glashow, Yanagida [64]	0.1	0.04
	Mei, Xing [65] (normal hierarchy)	0.07	0.02
*Albright,hep-ph/0407155	(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
	Anarchy		
	de Gouvêa, Murayama [66]	> 0.1	> 0.04
	Renormalization group enhancement		
	Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Observed oscillation parameters have already eliminated the "old" set of GUT Models

Many new models are now in the literature. Measurements of θ_{13}, the CP phase δ, and the mass hierarchy, will discriminate between them.

Predictions for θ_{13} are all over the map. It is crucial to pin down the order of magnitude for this parameter… and the smaller it gets the more interesting and constraining it becomes.

US APS Multi-Divisional Study on the Physics of Neutrinos: Main Questions

- *What are the masses of the neutrinos?*
- *What is the pattern of mixing among the different types of neutrinos?*
- *Are neutrinos their own antiparticles?*
- *Do neutrinos violate the symmetry CP?*
- *Are there "sterile" neutrinos?*
- *Do neutrinos have unexpected or exotic properties?*
- *What can neutrinos tell us about the models of new physics beyond the Standard Model?*

APS Multi-Divisional Study on the Physics of Neutrinos – Components of the Program

An expeditiously-deployed reactor experiment with sensitivity down to $\sin^2 2\theta_{13} = 0.01$

A timely accelerator experiment with the possibility of determining the character of the mass hierarchy

A megawatt-class proton driver and neutrino superbeam with an appropriate large detector capable of observing CP violation

If $\sin^2 2\theta_{13} < 0.01$, a neutrino factory will be needed

Fermilab and Neutrinos

Fermilab is host to the US accelerator-based neutrino program

MiniBooNE: LSND oscillation test
MINOS: Long-baseline, atmospheric neutrino mass scale (Talk: S. Kopp)
MUCOOL: Neutrino Factory R&D
MIPP: (partial motivation): Particle production (ν beam systematics)
Minerva: (neutrino cross-sections)

This suite of experiments provides a cutting-edge World-class experimental program that is a key part of the Global neutrino program.

Fermilab Long Range Planning Report

The basic recommendation of the Fermilab Long-Range Planning Committee: Aggressively pursue two options for Fermilab's future: A LC & a high-intensity Proton Driver → World-Class Neutrino Program.

Proton Driver Recommendations

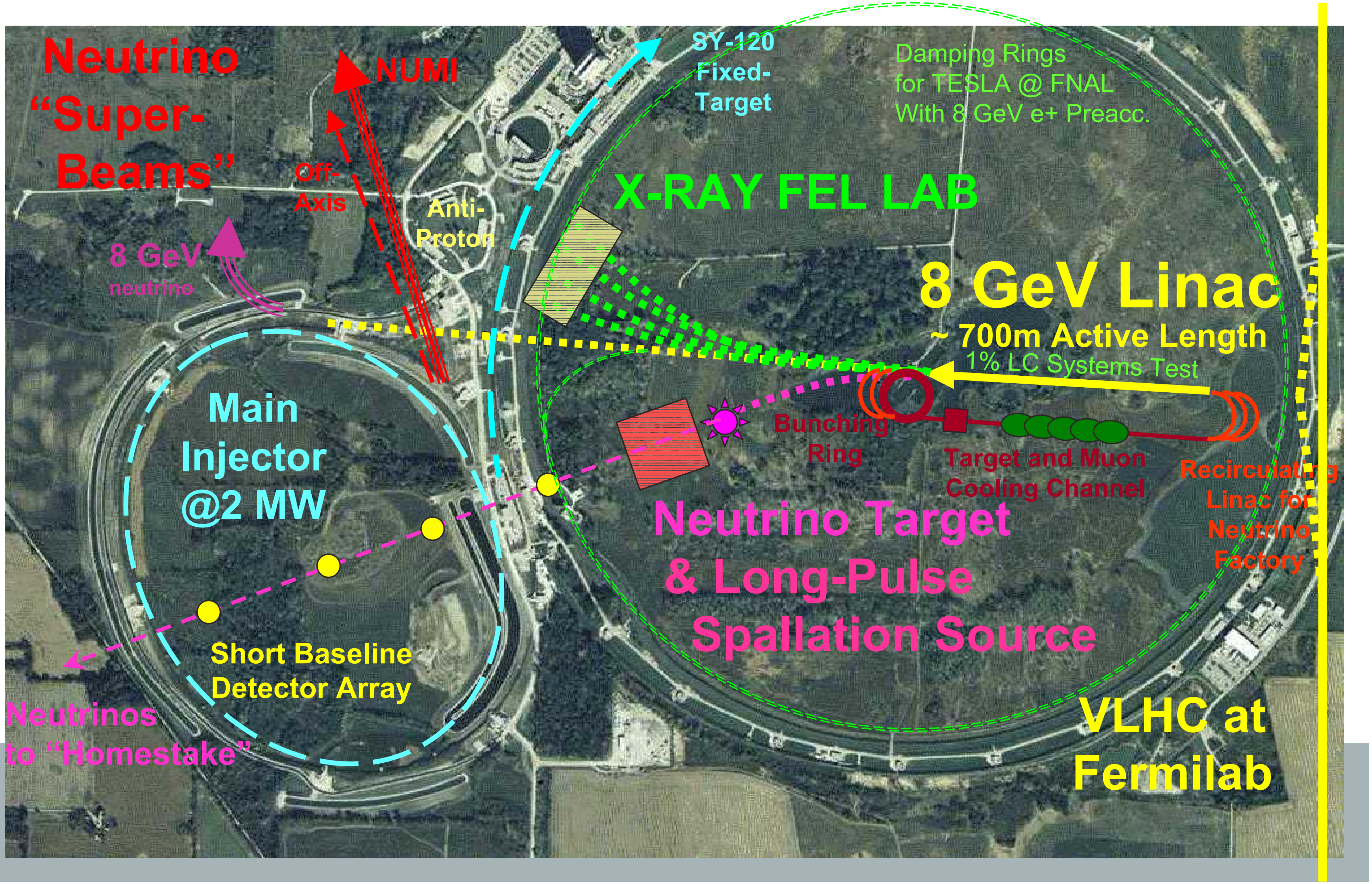
"We recommend that Fermilab prepare a case sufficient to achieve a statement of mission need (CD-0) for a 2 MW Proton Driver."

"We recommend that Fermilab elaborate the physics case for a Proton Driver & develop the design for a superconducting linear accelerator to replace the existing Linac-Booster system."

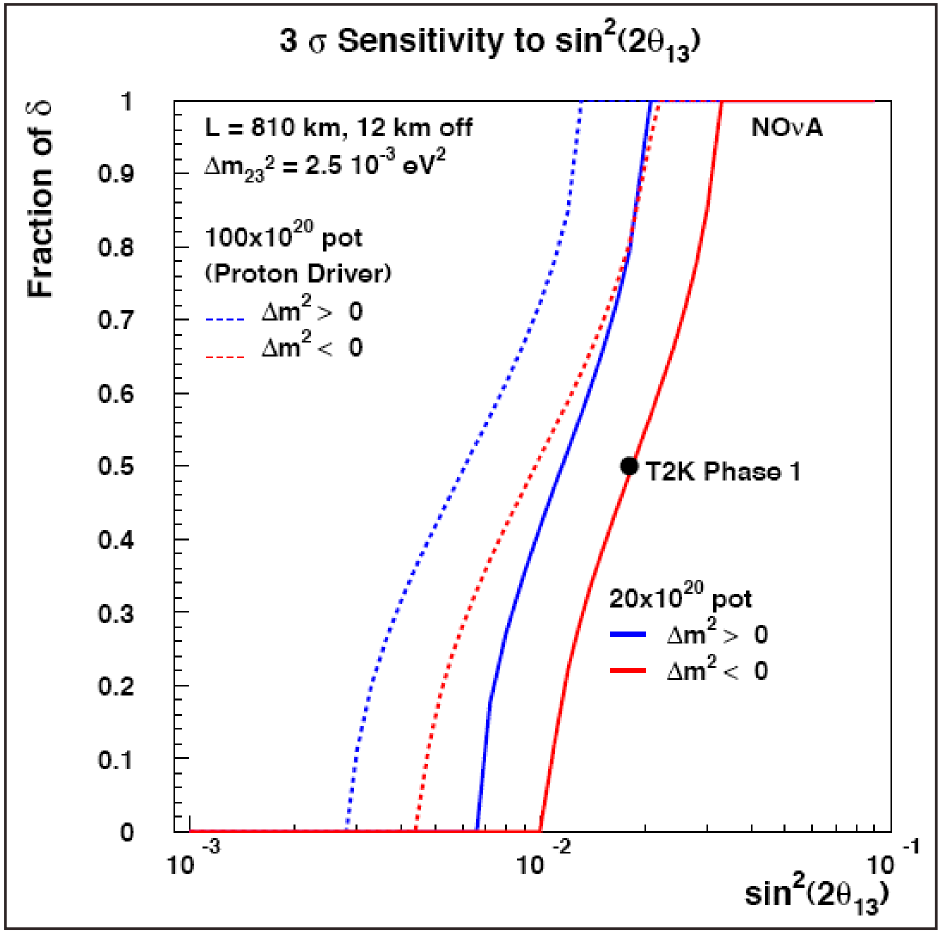
The Fermilab Director has subsequently requested

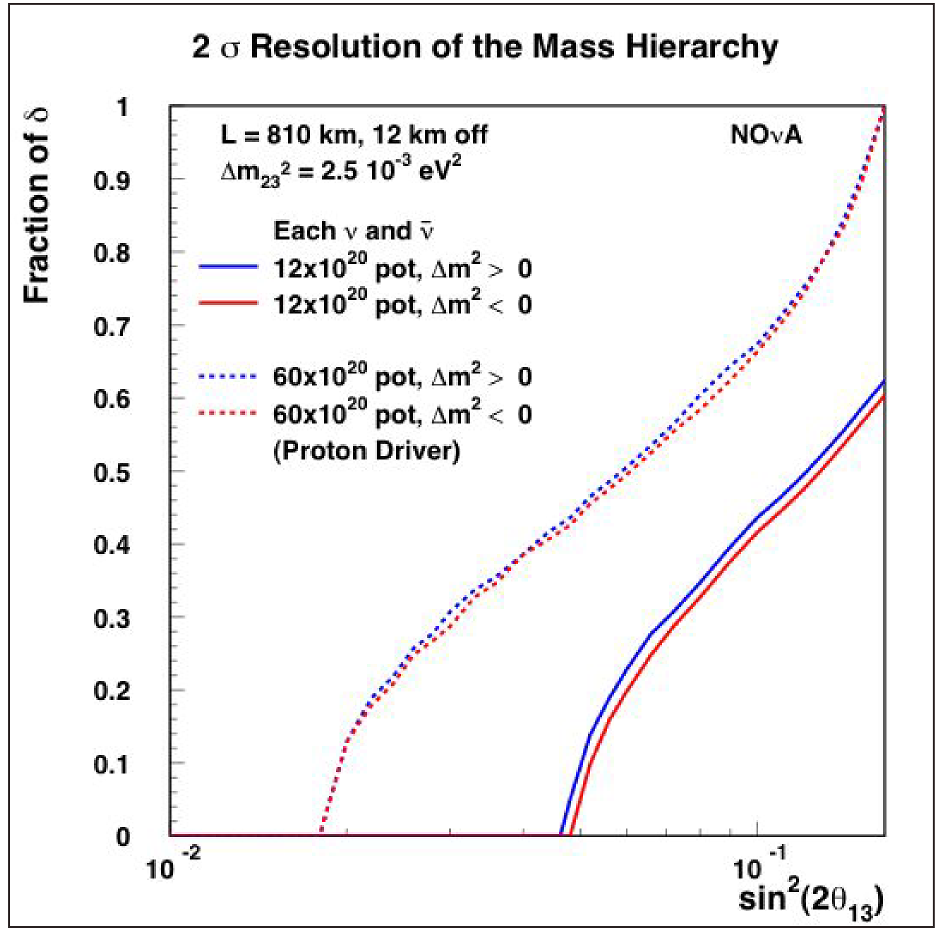
"Preparation of documentation sufficient to establish mission need for the Proton Driver as defined by the Department of Energy CD-0 process."

A New Fermilab Proton Driver would offer Flexibility for the Future Physics Program in General, & the Neutrino Program in Particular



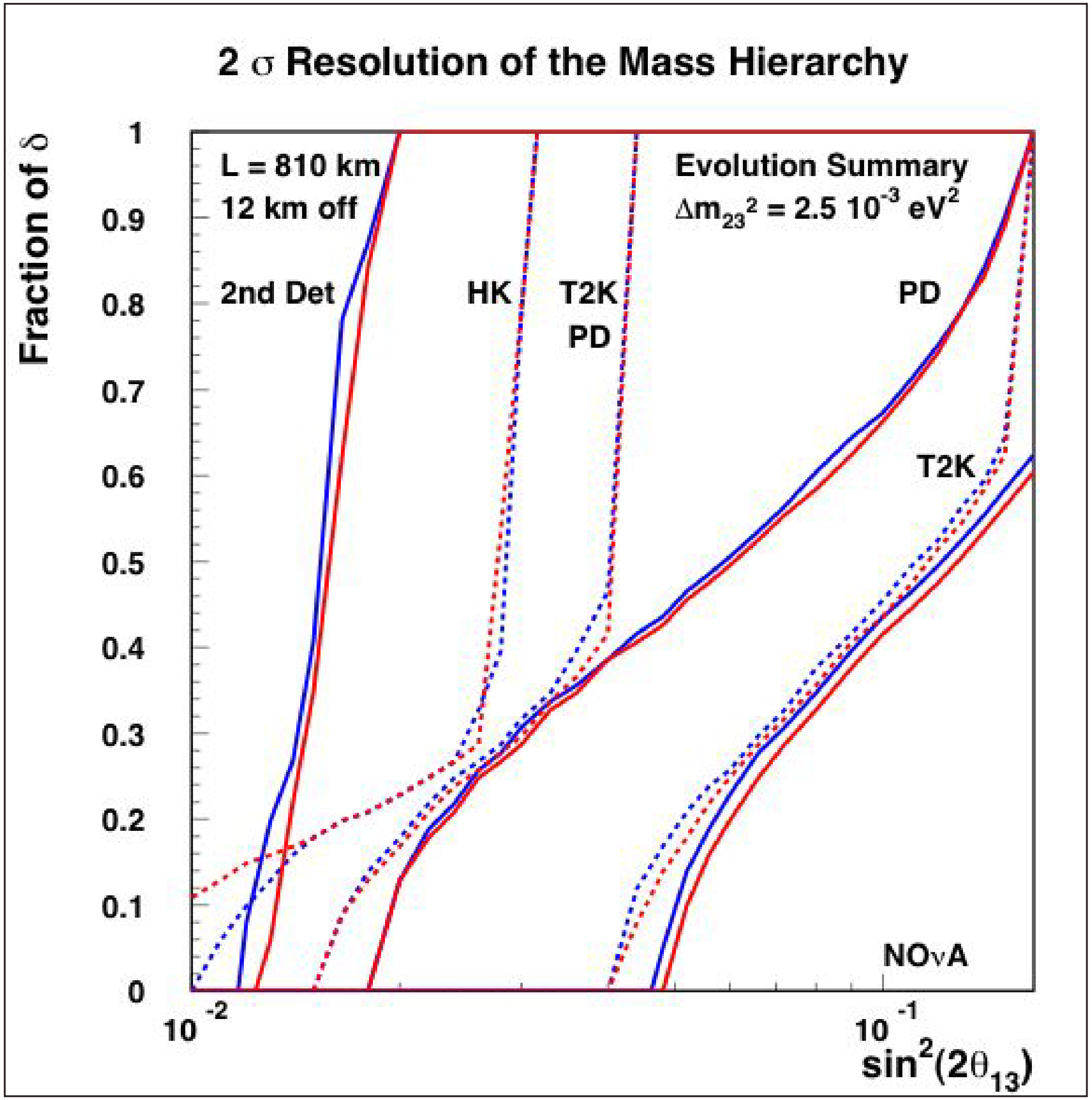
The Impact of a Proton Driver with NOνA





With the proposed 50 kt off-axis experiment (NOνA), a 2MW Proton Source would significantly improve the θ_{13} sensitivity (post-K2K), and greatly enlarge the region of parameter space within which the mass hierarchy can be determined.

Possible Longer-Term: Proton Driver + SuperNOνA

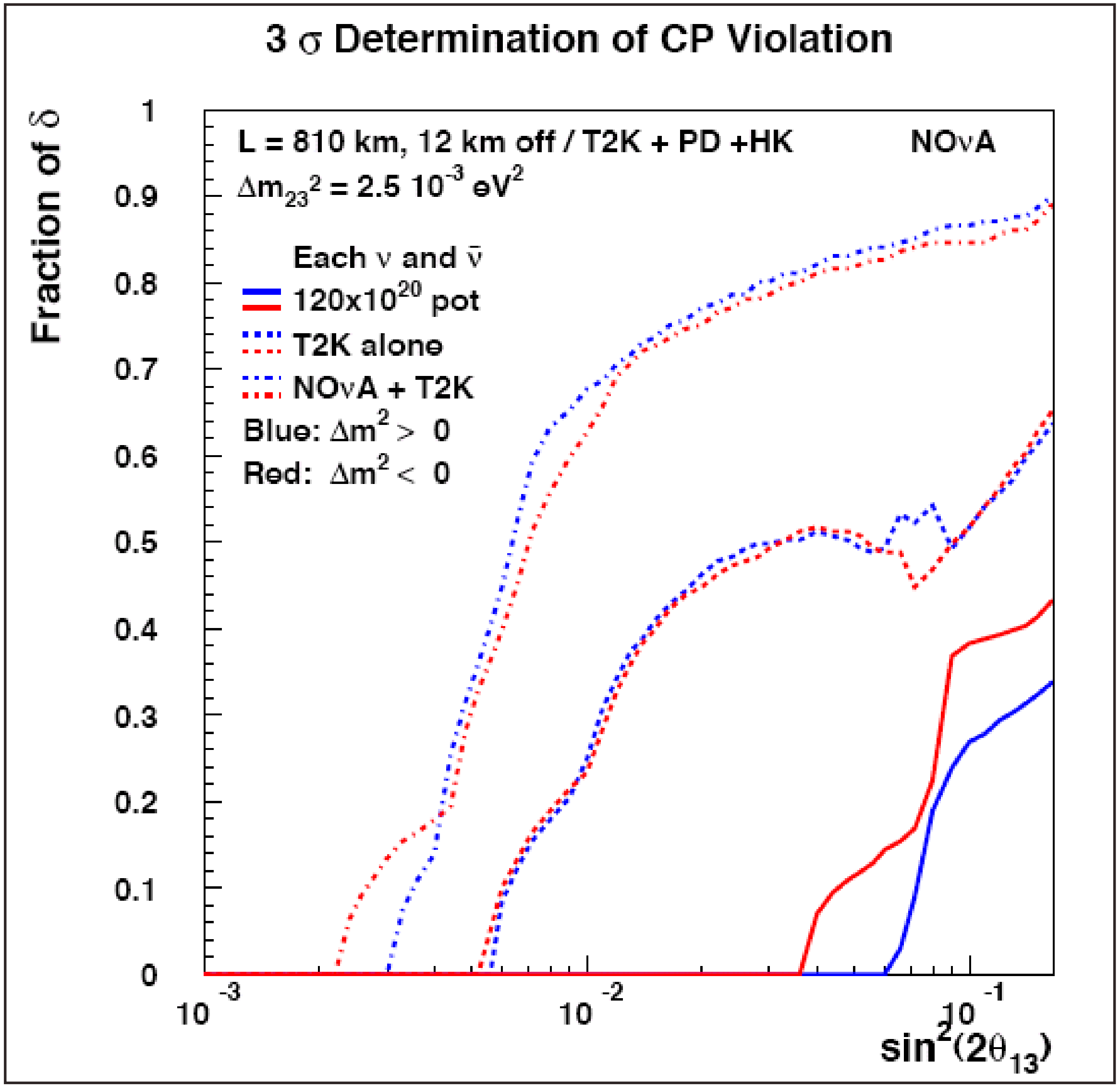


A plausible sequence of long-baseline Superbeam steps would be:

1. T2K
2. Fermilab PD (OA) Experiment
3. T2HK (Upgraded beam)
4. Fermilab PD with 2nd Detector

Lots of variants (BNL wideband beam idea, European neutrino program, Beta Beam ?)

Possible Longer-Term: CP Violation



A 2MW Proton Source with NOνA allows a first look for CP Violation over a small region of parameter space.

The sensitive region is greatly extended by combining NOνA with T2HK

If $\sin^2 2\theta_{13} < \sim 0.01$ we will need something beyond Superbeams

The Broader Neutrino Program

The Booster-Based ν Program is limited by proton economics and this will get worse when the NuMI program begins.

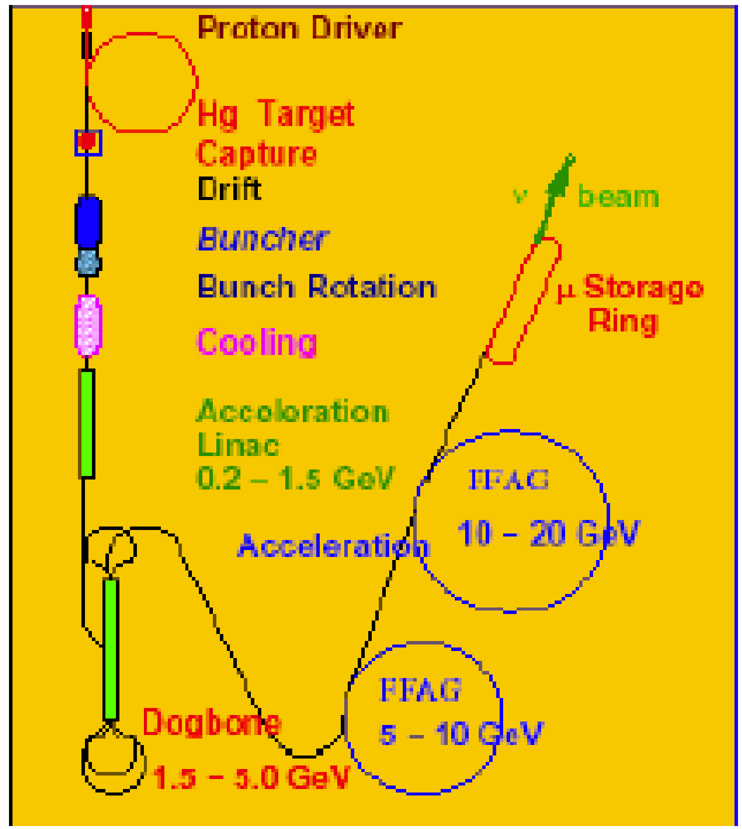
An upgraded proton driver will provide flexibility to exploit big surprises (for example, a positive MiniBooNE result) ….

… and opportunities for new “small” neutrino experiments.
Examples: low energy neutrino cross-section measurements, neutrino magnetic moment and exotic interaction searches.

The neutrino program that could be supported by a 2MW proton driver is likely to consist of a multi-phase program with at least a handful of experiments that provide world class cutting edge physics for a period of a couple of decades or longer.

Neutrino Factory Ingredients

- *Neutrino Factory comprises these sections*
  - *Proton Driver*
    - *primary beam on production target*
  - *Target, Capture, and Decay*
    - *create π; decay into μ*
  - *Bunching and Phase Rotation*
    - *reduce ΔE of bunch*
  - *Cooling*
    - *reduce transverse emittance*
  - *Acceleration*
    - *130 MeV $\rightarrow$ 20 GeV*
  - *Storage Ring*
    - *store for 500 turns; long straight*

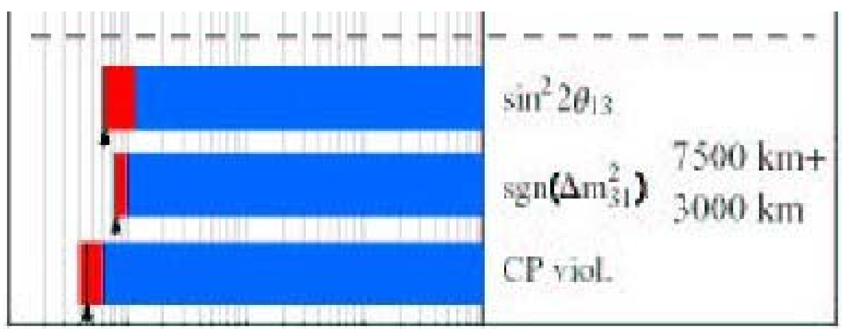


US Design schematic

A MW-Scale Proton Driver provides a path to the Ultimate Neutrino Oscillation Physics Reach at a Neutrino Factory

The full physics program (Establishing the magnitude of θ_{13}, determining the mass hierarchy, & searching for CPV) can be accomplished if $\mathrm{Sin}^2 2\theta_{13} > O(10^{-4})$!

Huber, Winter; Phys. Rev. D68, 2003



10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}

$\mathrm{Sin}^2 2\theta_{13}$

Note: As $\theta_{13} \to 0$, $P(\nu_e \to \nu_\mu) \not\to 0$. If $\mathrm{Sin}^2 2\theta_{13} < O(10^{-4})$ a Neutrino Factory will make the first observation of $\nu_e \leftrightarrow \nu_\mu$ appearance & provide a very important test of three-flavor mixing.

Neutrino Factory R&D

Design: Two serious engineering studies have established feasibility and performance, and identified the required R&D program. Biggest outstanding design issue is cost optimization.

Hardware: Two areas needing substantial R&D are Targetry and Ionization Cooling. New acceleration ideas should also be explored when resources permit.

Targetry: Successful initial program has shown liquid Hg jet is likely to work. Preparing for a convincing test (P186 at CERN) in a couple of years.

Ionization Cooling: Component development (MUCOOL) advanced, and international Muon Ionization Cooling Experiment (MICE) has Scientific Approval at RAL.

Neutrino Factory Design and Cost

The Neutrino Factory Study 2 cost estimate was dominated by 3 ~equally expensive sub-systems: (i) Phase Rotation, (ii) Cooling Channel, (iii) Acceleration.These accounted for ~3/4 of the total cost.

In the last few years we have focused on developing potentially cheaper solutions for all three sub-systems. Factors of two in cost reduction for each of these sub-systems may be possible.

	All ($M)	No PD ($M)	No PD & Tgt. ($M)
FS2	1832	1641	1538
FS2a-scaled (%)	67	63	60

In 1-2 years time hope to launch a "Study 3" focused on a cost-optimized design.

Summary

Neutrino Oscillation Physics is exciting. To make progress we will need multi-MW multi-GeV proton sources ($\rightarrow$ Neutrino Superbeams), and probably ultimately a Neutrino Factory.

A 2MW proton driver at Fermilab would provide, for decades to come, an exciting World Class neutrino physics program for the laboratory and its user community.

A unique long-baseline neutrino oscillation physics program would provide the main thrust, but the proton driver could also support a more diverse program of world class experiments.